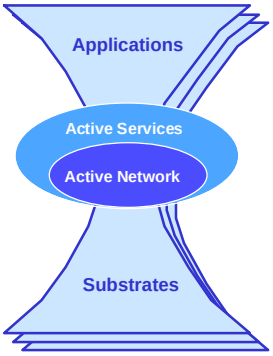


From Internet to … Active Net

Dr. David Tennenhouse
Information Technology Office

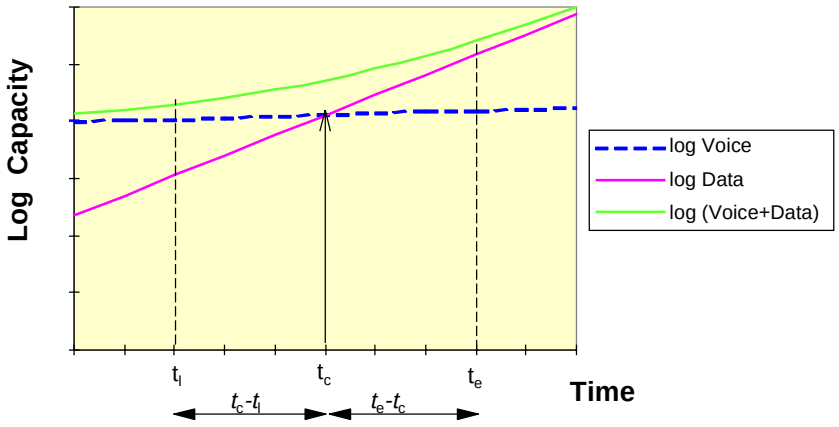
1

OUTLINE

- **Where are we going?**
- **What are the issues / drivers?**
- **How do we get there?**

2

VOICE/DATA TRANSITION MODEL



3

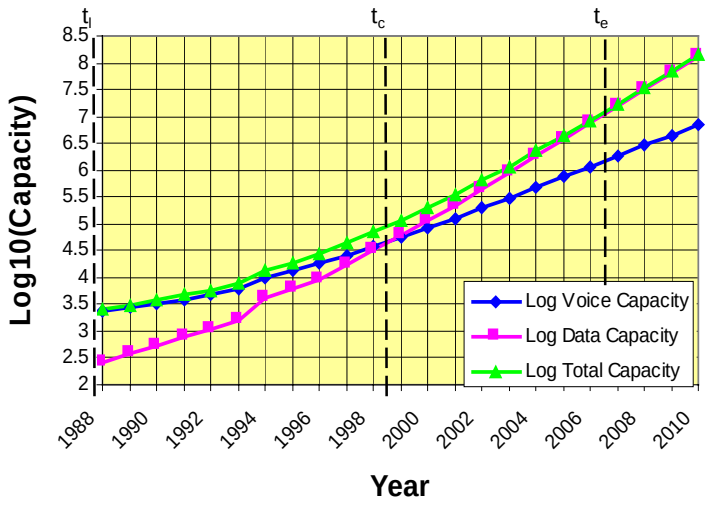
A VOICE/DATA TRANSITION MODEL

Assume a backbone network supporting: voice services based on traditional circuit switching, growing in their capacity demand at a constant annual rate r_v; and a suite of data services based on packet switching, growing at a different constant rate r_d.

- **Define the following quantities of interest:**
  - t_l, the lead-user point; Packet-data traffic is 10% of the total capacity.
  - t_c, the crossover point; Both types of service require the same capacity.
  - t_e, the eclipse point; Packet-data traffic consumes 90% of the overall backbone capacity.
  - t_c- t_l, Interval from the lead-user point to the crossover point.
  - t_e- t_c, Interval from the crossover point to the eclipse point.

4

TRANSITION MODEL "RESULTS"



5

"RESULTS" (based on Two POPs)

Industry-wide model results

t_l	t_c	t_e	t_c-t_l	t_e-t_c	r_v	r_d	α(1996)
1988	Nov 1998	2007	10 yrs	9 yrs	0.38	0.69	1.97

Idle voice scenario

t_l	t_c	t_e	t_c-t_l	t_e-t_c	r_v	r_d	r_{total}
1988	Sep 1997	2008	9 yrs	11 yrs	0.088	0.69	0.27

Accelerated data growth scenario

t_l	t_c	t_e	t_c-t_l	t_e-t_c	r_v	r_d	r_{total}
1988	Feb 1997	2001	9 yrs	4 yrs	0.088	0.988	0.45

6

IMPLICATIONS

Suddenness of the transition may be a key determinant of the outcome

- **RBOCs vs. ISPs**
  - Who will own the inter-exchange switches / routers?
  - Who will supply inter-office transmission?
  - Who will service the last mile?
- **Equipment Vendors**
  - What are the implications for the traditional switch vendors?
- **What is the Role of Internet Telephony?**
  - How fast does it happen? Why?

7

POLICY CONSIDERATIONS

- **Lagging Revenue Transition**
  - What dangers does this present?
- **Local Distribution**
- **Bundling of Voice and Data**
- **Decouple regulation of services from regulation of carriage/spectrum**

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THE POOL TRIPLE

"An uncentralized set of communications systems can function as a single system only if traffic on each network can move through interfaces onto the other networks. The critical requirements are three: the right to interconnect, conformity to technical standards that make interfacing possible, and a directory system."

– Technologies of Freedom (1984) by Ithiel de Sola Pool

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OUTLINE

- **Where are we going?**
- **What are the issues / drivers?**
- **How do we get there?**

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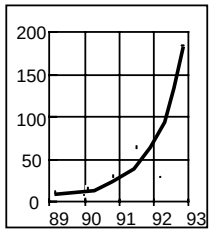
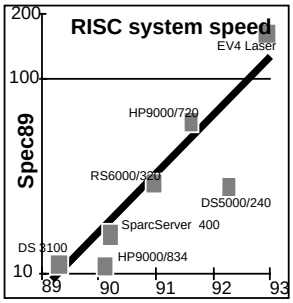
THE PROBLEM IN A NUTSHELL



Growth is exponential
plot on semi-log scale



- **Technologies are moving fast**
  - Computing customers benefit quickly (price **& performance**)
  - **Communications customers do not**
- **How do we get the NII onto the curve?**
  - How do we keep it there?

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VERTICAL COUPLING OF SUPPLY & DISTRIBUTION

- **Examples (Radio, television, Cable Satellite, telephone, Newspaper)**
- **Each information supplier has its own distribution channel / network**
  - Similar to gas / water / electricity
- **Appliances are tailored to the medium**
- **Vertical integration of information services / channels / appliances**
- **Markets are segmented by tightly coupled architectures**

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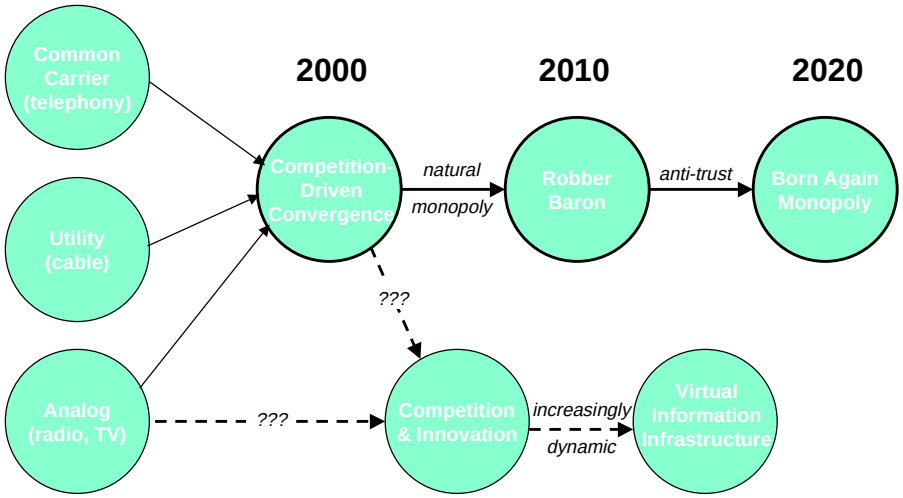
TRANSITION SCENARIOS



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WHAT ARE THE DRIVERS?

- **Competition?**
- **Digitization.**
- **Virtualization!**
  - Software, Software, Software
    (What enabled competition?)

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AN INFRASTRUCTURE TAXONOMY

Infrastructure	Competitive	Generic	Decoupled
Cable, Utilities, old AT&T Monopoly			
Radio, TV	√		
Local access to long-distance telephony			√
	√		√
Convergence model	√	√	
Vertically integrated monopoly		√	
Roads, US Mail		√	√
Package Transport (Rail, Air, etc.)	√	√	√

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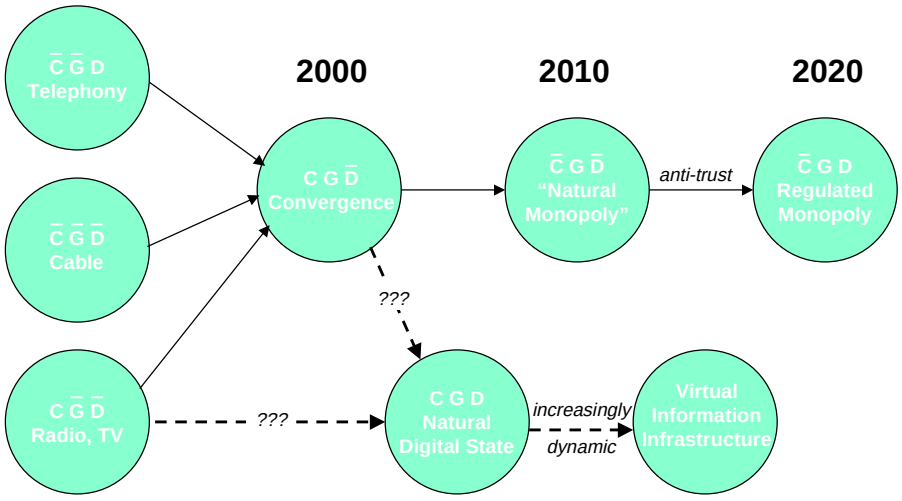
TRANSITION SCENARIOS



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WHY CGD? –WHAT'S DIFFERENT ABOUT INFORMATION?

Implications	Digital Fundamentals: Symbolic representation	Conversion	Encapsulation	Fragmentation	Time independence	Dynamic resource allocation
Competition & Innovation	√	√				
Generic distribution	√	√	√	√		
Decoupling supply/ appliances	√	√	√	√	√	√

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DECOUPLING – DRIVERS

- **Consider the Transportation Network … Carriage & Content are Decoupled**
- **Why?**
  - To suppliers, distribution is a necessary evil.
- **What are the enablers?**
  - Packaging – Flexibility as to size & shape
  - Brokerage – Flexible Sharing (Car, Truck, UPS, Mail)
  - Diversity – Safety in numbers

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CHALLENGES

- **Decoupling Content & Carriage**
- **Decoupling Appliances & Carriage**
- **Embracing Diversify and Innovation**

DECOUPLING CONTENT & CARRIAGE

- **To content providers …**
  - Distribution is a necessary evil (today)
- **To carriers …**
  - "moving bits" is a commodity business
    But … What's wrong with commodities?
- **Policy Issues**
  - Decoupling content and carriage regulation
  - Market regulation vs service regulation
  - What about natural monopoly?
    - economy of scale vs economy of innovation

CONTENT & CARRIAGE – TECHNOLOGY

- **Local Distribution – Cellularization**
  - Common basis for telco, cable, wireless solutions
- **Making spectrum fungible**
  - Source Coding vs Channel Coding
  - SpectrumWare
    - software based wideband processing
- **Encourage alternative technologies for alternative circumstances**
  - Metric: Hz/person
  - Urban: Enclosed spectrum
  - Rural: Terrestrial and satellite RF

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DECOUPLING APPLIANCES & CARRIAGE

- **Strategy / Policy Challenge: Why are set top boxes so !@$# expensive?**
  - Open market for inter-operable appliances
  - Appliance ownership? Distribution channels?
- **Technology Challenge**
  - Leverage active technologies, such as Java!
  - Accommodate diversity
    - networks, computers, software, etc.
  - Configuration management.
    - take it home from the store and it works.
- **Home Information Infrastructure is substantial.**
  - CDs, TVs, VCRs, CamCorders, etc. are going digital.
  - Ultimately these communicate with each other.
- **The HII will drive:**
  - Consumer Informatics.
  - The reverse channel.
  - Residential bandwidth on demand.

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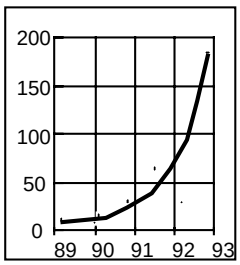
EMBRACING DIVERSITY

- **Innovation leads to heterogeneity!**
  - Each RBOC is planning its own architecture.
  - Cable holdings are geographically dispersed.
  - Cellular networks are going digital – in 4 flavors!
- **Don't fight it — MASTER IT!**
  - Provide the same look and feel
    – not the same technology.

WHAT'S ENABLES ALL THIS? SOFTWARE!



Growth is exponential
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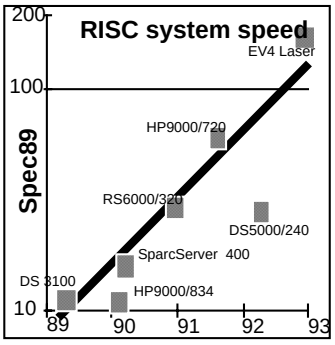
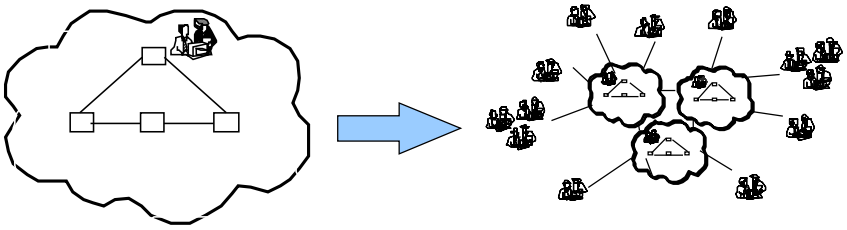


- **Systems are increasingly software-driven**
  - Software implements conversion / configuration functions.
  - Processing ability grows exponentially.
  - Cost of diversity / dynamic configuration is in free fall.
  - What is the role of (software) standards?

CHANGING THE INFRASTRUCTURE INNOVATION PROCESS



Today

Deployment of new functions driven by hardware vendors and operators.

Future

Driven by users and software vendors.

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OUTLINE

- **Where are we going?**
- **What are the issues / drivers?**
- **How do we get there?**

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WHAT IS ACTIVE INFRASTRUCTURE ABOUT?

Approach to networking that allows each group of users to tailor the shared infrastructure to their requirements

- Ability to dynamically mold (*program*) the surrounding network infrastructure
- Massive increase in degree, sophistication and control of software deployed *inside* the network

Infrastructure that can turn on a dime

Not just where we go, but how fast we get there!

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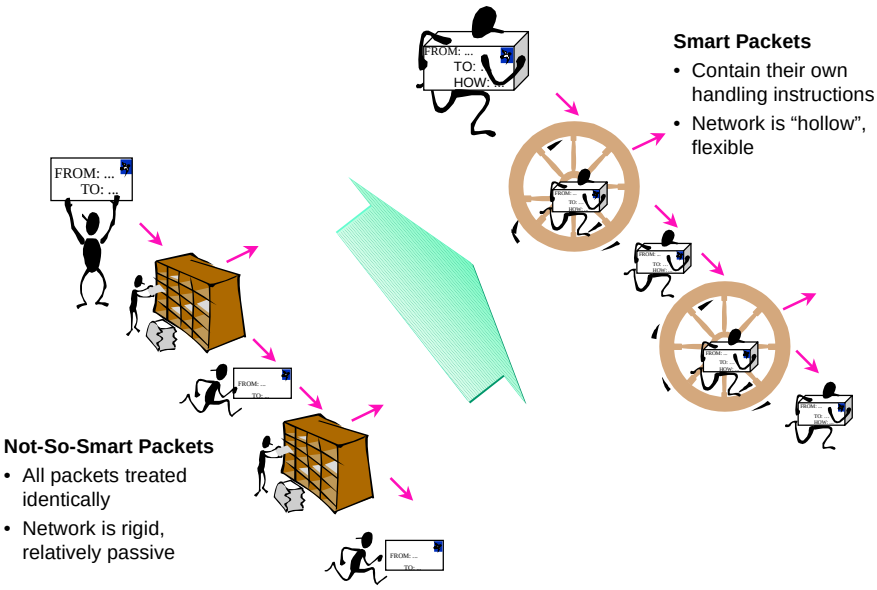
ACTIVE NETWORKS



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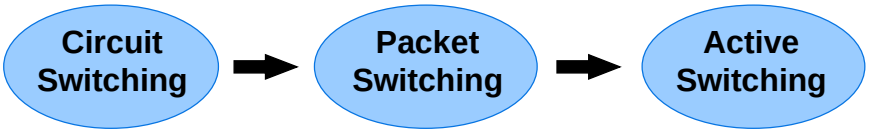
ACTIVE NETWORKS

- **Active in two ways:**
  - Network performs user-specific computations on packet data
  - Users supply code that is executed in the switches / routers
- **Computation *in-line* with communication**
- **Massive increase in degree & sophistication of software deployed *inside* the network**



"Pull" => Lead Users

Lead users are inventing ad-hoc strategies to perform computation *within* the network

- **Fire walls**
  - Masquerade as routers, but are application-specific…
- **Web proxies**
  - An increasing fraction of web pages are dynamic…
- **Mobile / Nomadic computing**
  - Agents, gateways, proxies, routers, etc.

Network-based computation is happening! We need to deal with it!

"Push" => Active Technologies

- **Java is one of many *active technologies***
- **What are they?**
  - Mechanisms that allow users to inject custom *programs* into *shared* resources
- **Where have they come from?**
  - Printing – Postscript
  - Parallel Processing – Active Messages
  - Operating Systems – Sandboxing
  - Programming Languages – Java, Tcl.
  - Compilers – "on the fly" compilation
  - Formal Methods – static checking, SCC, etc.

- **What is new?**
  - Safety, efficiency and mobility now addressed in concert

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REMAINDER OF THIS TALK…

- Active Networks: What / Why?
- **What's Happening at MIT?**
- **What is All This Good For?**
- **Work Elsewhere?**
- **Broader Implications?**

Key Players at MIT

- John Guttag (Principal Investigator); Steve Garland (Co-PI)
- David Tennenhouse (provocateur in absentia)
- Graduate Students
  - David Wetherall
  - Ulana Legedza
  - Li-wei Lehman
  - Dave Evans

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THREE THRUSTS OF MIT'S ACTIVE NETWORK RESEARCH

- **Making it possible to build active nets**
  - Ease of programming
  - Protection and security
  - Efficiency
- **Understanding opportunities**
  - Exploiting computation and storage inside the network
  - Introduction of many specialized services
- **Understanding performance issues**
  - Bandwidth to the host is not the issue
  - Useful information to the application is what matters
  - New cost / benefit models are required

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ALTERNATIVE ARCHITECTURES

- **Discrete Approach – programmable routers / switches**
  - Maintain packet abstraction
  - Add "back door" for injecting programs into nodes
  - Technology transfer is straightforward
- **Integrated Approach – based on capsules**
  - Nodes exchange encapsulated program fragments
  - Routers become capsule execution engines
  - Capsules also carry embedded data (a la Postscript)
- **Hybrids**
  - Capsule classes are demand loaded and/or cached

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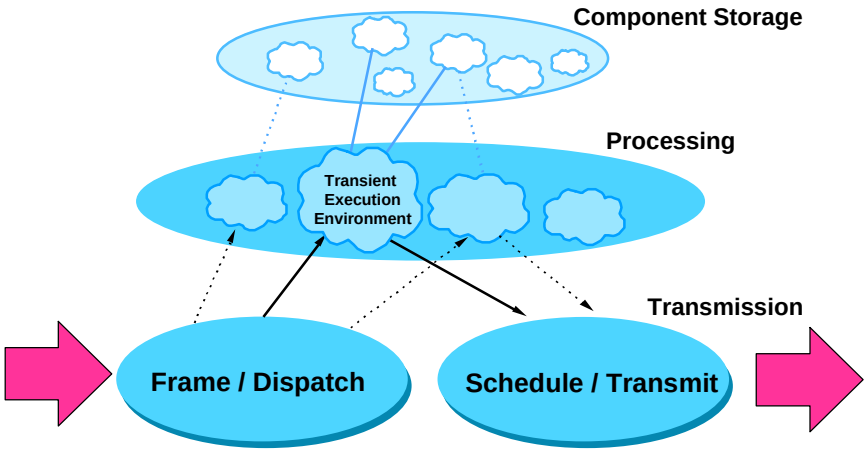
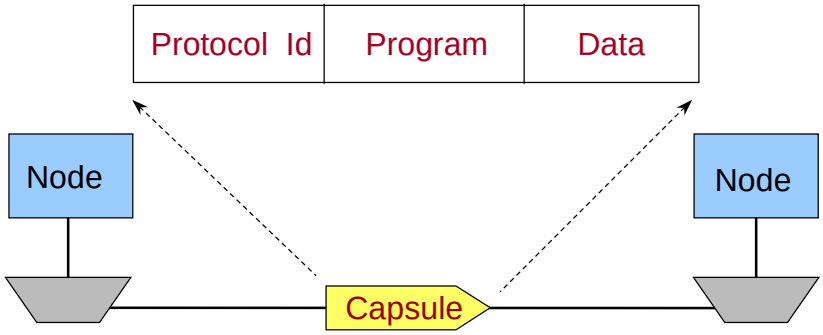
ACTIVE NODE ORGANIZATION



CAPSULES ARE GENERALIZED PACKETS



- Capsules don't usually carry the program…
- Carry a description (e.g., a fingerprint) instead
  - Critical that this is more than a name
  - Prevents protocol spoofing

PROGRAMMING WITH CAPSULES

- **Basic instruction set** JAVA
  - Arithmetic, branching, stack/heap…
- **Foundation components** JAVA ANTS
  - Access to node API / embedded OS
- **Demand loading / caching of user components** JAVA ANTS
- **Soft state** ANTS ANTS Users
  - Connections, flows, rendezvous…
  - Data caches for web, multi-cast, information fusion, etc.
- **Persistent state** ?

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ANTS – ACTIVE NODE TRANSFER SYSTEM

- **Capsule assembly, transfer & interpretation**
  - Java-based
- **Base classes:**
  - Capsule, node, protocol, application
- **Status:**
  - Just a skeleton; still fleshing out functionality
  - Later – recode some portions for performance
  - Parallel work on static checking and resource management

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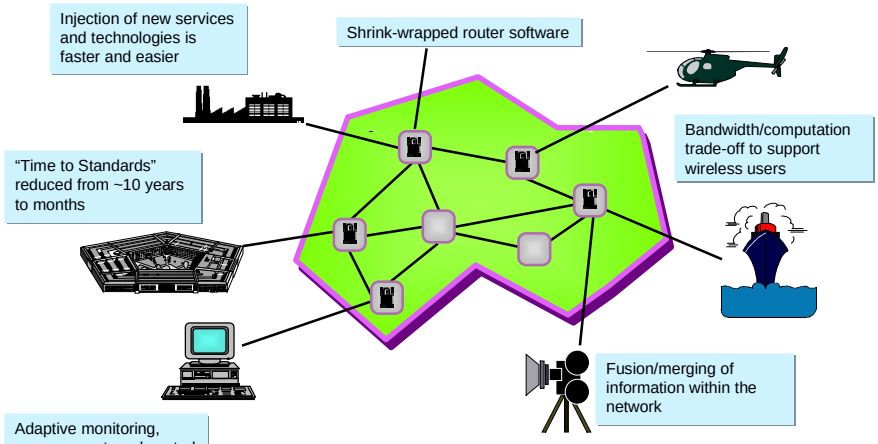
ANTS GLOSSARY

- **Node**
  - Host machine or router
- **Capsule**
  - Generalization of packet
- **Protocol**
  - Collection of related capsule types
  - Unit of network customization and protection
- **Application**
  - Connects to a node on a port
  - Uses capsules for customized network service
- **David Wetherall**
  - Primary designer and implementor of ANTS

NODE OPERATING SYSTEM

- **Hosts user-defined protocols, providing**
  - Soft-storage, routing, “eval”, ...
  - Each protocol with its view of the network
- **Protects the integrity of the network:**
  - Executes untrusted capsule routines
  - Limits their resource consumption
    - Still an open research problem
- **Code distribution**
  - Some guaranteed present at each node
  - Some transferred using code distribution protocol
    - Demand loading, pre-fetching, caching all used
    - Well-suited to flows

WHAT IS ALL THIS GOOD FOR?



Network infrastructure that can instantly be tailored to mission requirements

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ACTIVE RELIABLE MULTICAST (ARM)

(Li-wei Lehman, MIT)

- **Novel Features**
  - NACK fusion / suppression
  - Data caching at strategic locations
  - Partial multicasting for scoped retransmission

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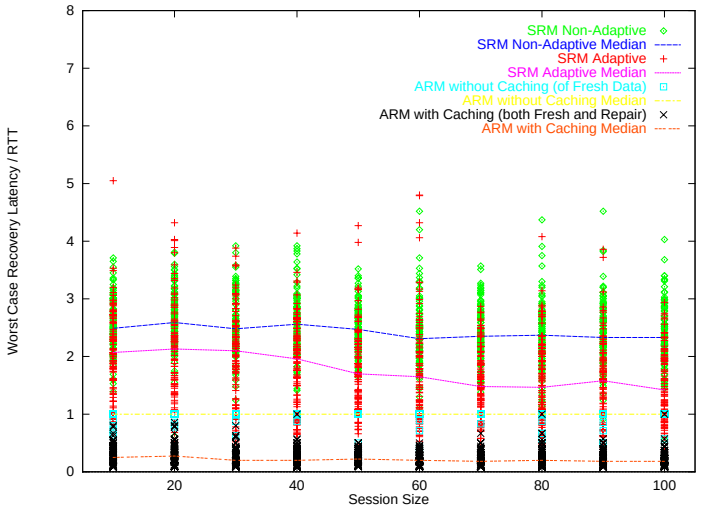
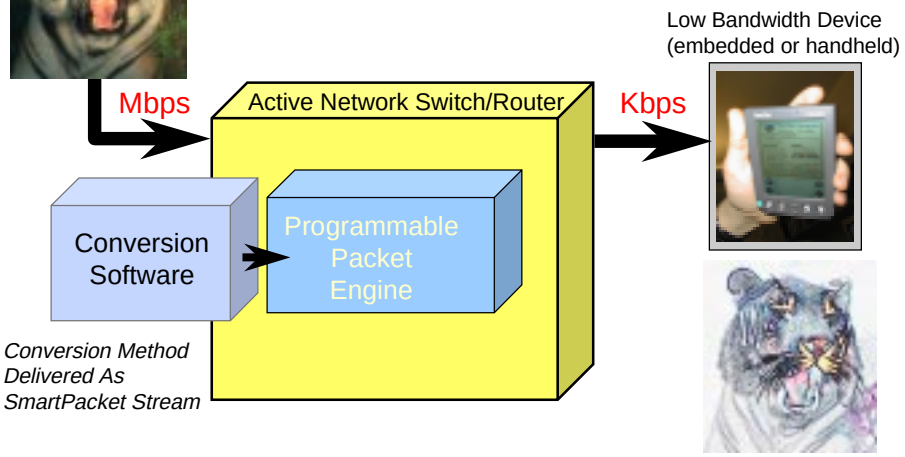
WORST CASE RECOVERY LATENCY



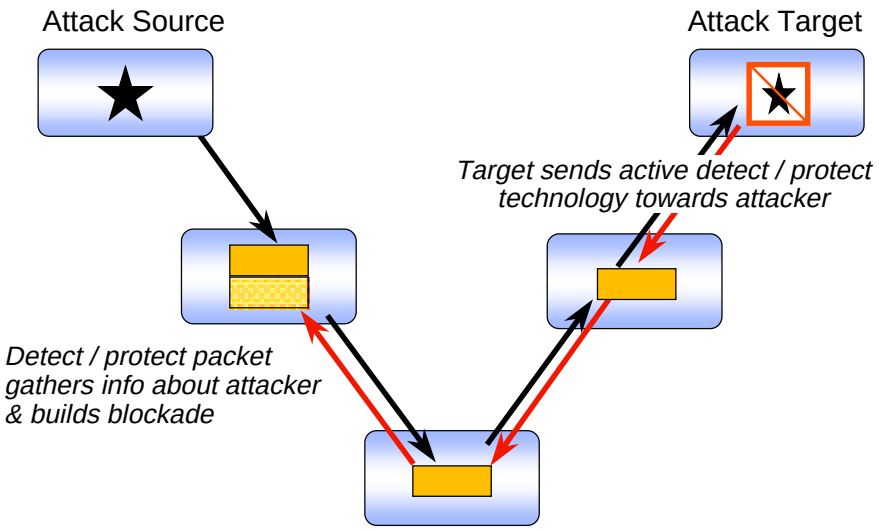
ARM vs. SRM worst case recovery delay (random loss, 1000 nodes, degree 4)

TRADING COMPUTATION FOR BANDWIDTH

Large Data Stream Reduced to Small One at Nearest Capable Network Point



NETWORK ATTACK TRACEBACK



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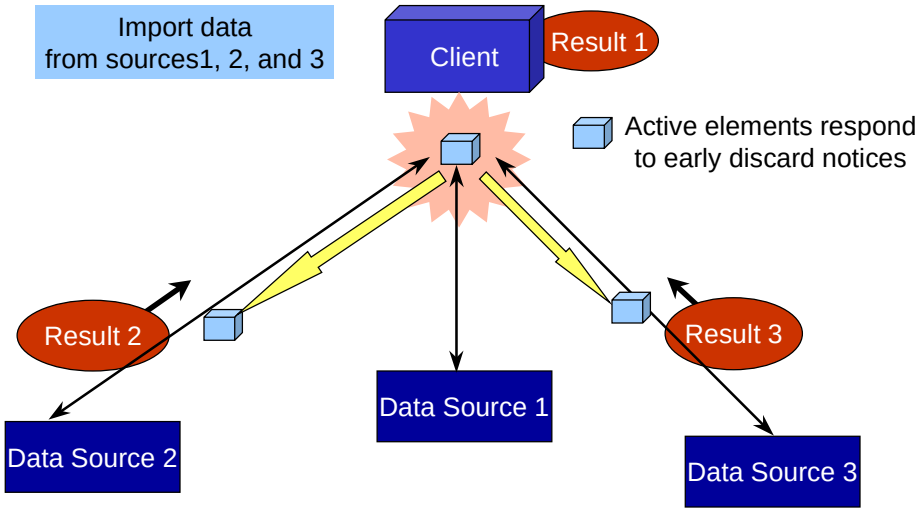
PRUNING / CANCELING PARALLEL QUERIES



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WORK ELSEWHERE / RELATED ACTIVITIES

- **U. Penn / Bellcore – SwitchWare & Protocol Boosters**
- **BBN – Smart Packets**
- **Open Group RI – CONVERSANT**
- **Columbia – NetScript**
- **Georgia Tech – CANEs**
- **TASC – PANAMA**
- **USC/ISI – Active Signalling**
- **UCLA – Adaptive Web Caching**
- **CMU – Application-Aware Nets**

Enabling Technologies

- **MIT – Exokernel & VCODE**
- **U. Arizona – Liquid Software**
- **U. Wash – SPIN**

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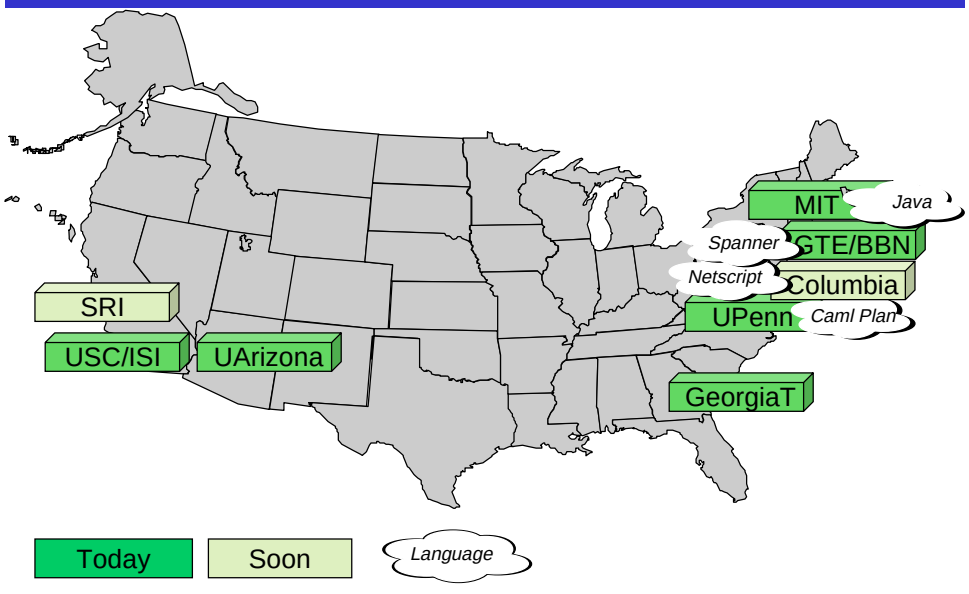
ACTIVE NETS TESTBED TODAY: THE ABONE



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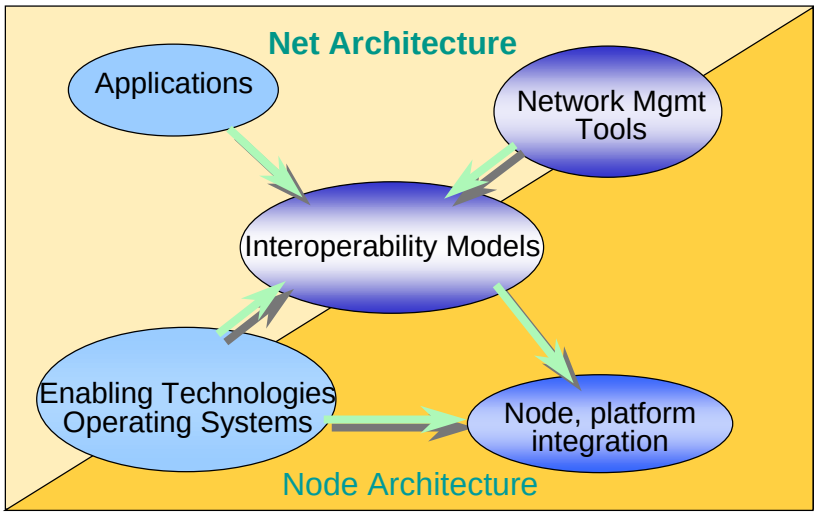
ARCHITECTURAL FRAMEWORK



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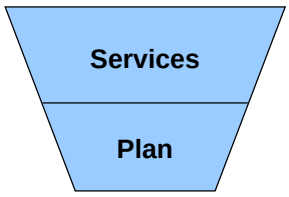
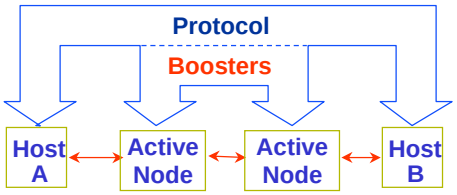
SwitchWare
University of Pennsylvania and Bellcore



- Safe programming languages; guarantees key invariants
- Integration between guarantees and cryptography
- Two-level approach:
  - PLAN: Programming Language for Active Networks
  - Interoperable services

Protocol Boosters
Bellcore



- Family of booster modules that can robustly adapt protocols to their environment
- OS and hardware supporting run-time booster insertion/removal and policy decisions

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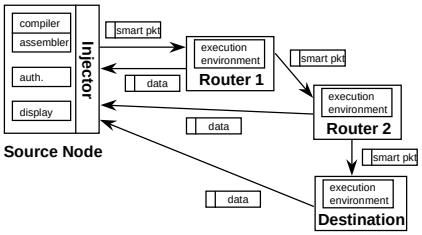
Smart Packets

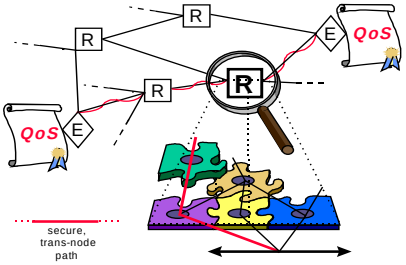
BBN Corporation



- Packets carry programs implementing extended diagnostic facilities
- Diagnostics customize themselves to platform and report on anomalous network behavior
- Packets encapsulated in Active Network Message Protocol (ANMP) with Router Alert IP Option

CONVERSANT: an Environment for Real-time, Secure Active Networks

Open Group Research Institute



- Java-based, composable building blocks ("graphlets")
- Named graphlets are carried "by reference" and resolved through recipient's trusted and preferred supplier(s)
- Secure, trans-node paths
- Mechanisms and policies for safe manipulation of imported graphlets and for controlled interference among paths

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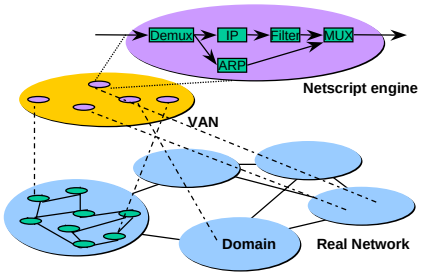
NetScript: A Language-Based Active Network Architecture

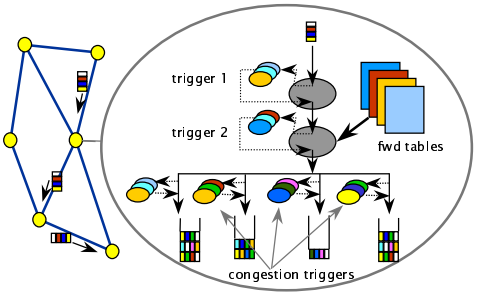
Columbia University



- Netscript dataflow language for programming Active Network (AN) engines and packet stream processing
- Virtual Active Network (VANs) abstractions define units of management and security
- Programmable nodes: active firewalls, active managers, intrusion detectors, etc.

CANEs: Composable Active Network Elements

Georgia Institute of Technology



- User-network interface based on functions applied to packets:

  forward, install state/method, invoke interpreter, etc.
- Functions customized via methods invoked at standard trigger points
- Fast-path optimization for 90% case
- Demonstrate mobility, multicast, other services

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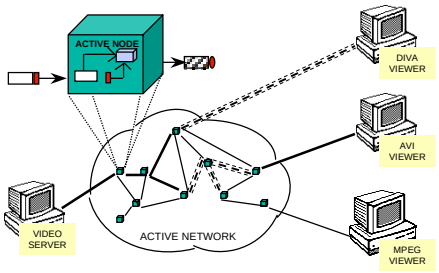
Protocol on Active Networks for Adaptive Multicast Applications (PANAMA)

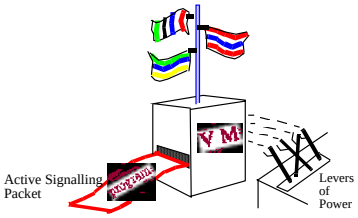
TASC, Inc.



- Configurable, active multicast protocol
- Self-identifying packets configure node behavior
- Analysis of optimal multicast code/function location

Active Signalling Protocol

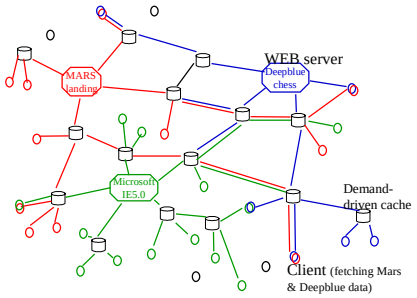
USC/Information Sciences Institute



- Support realtime applications in Internet: teleconferencing, distributed simulation
- Essential component of Internet resource reservation: setup protocol

Adaptive Web Caching

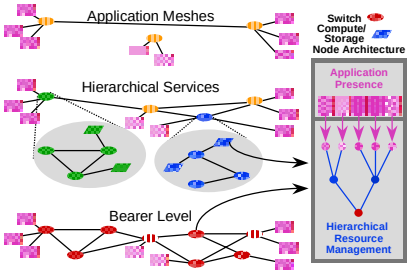
University of California, Los Angeles



- Development of self-organizing protocols and algorithms
- Demonstration of self-organizing system design principles in large-scale systems such as Web caching

Resource Management in Application-Aware Networks

Carnegie Mellon University



- Hierarchical resource management provides structured support for diverse collaborating and competing electronic services
- Application and service presence in the network supports application-tailored resource management and quality of service

ACTIVE NETWORKS – NUTSHELL SUMMARY

- **Packets become "smart" messages**
  - Carry code executed inside the network switches / routers
  - Routers are "hollow"
- **Move beyond packet switching**
  - Leverage computation / storage within the network
  - Network takes on many characteristics of an OS
- **Impact**
  - New applications
  - Standardize programming model instead of packet format

circuits → packets → capsules

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INTEROPERABILITY

- **Today … Packet Switching**
  same packet model everywhere
  - Common packet format…the IP Protocol
  - All switches / routers understand this format
- **Future…Active Switching**
  same programming model everywhere
  - Common program format…
  - Programs understand packet formats
  - Diversity in message syntax & semantics

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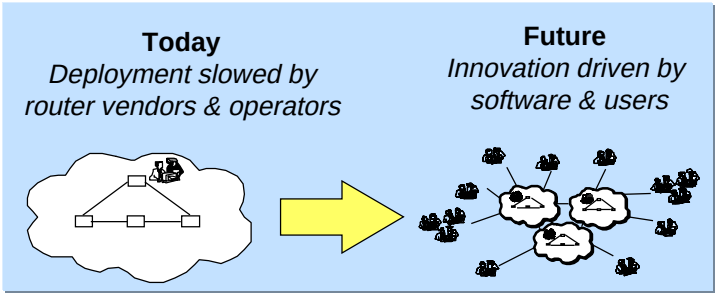
CHANGING THE INNOVATION PROCESS



Conventional nets rely on agreement about services
- Standardization a long and wrenching process

Active nets rely on agreement about model of computation
- A difficult design problem

Role of network designer
- Make it easy to add network services
- Not to define "right" set of network services

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THE REAL STORY: ACTIVE / MOBILE CODE

- **Premise**

  Java-enabled browsers are (at most) 5% of the story…

  How does widespread code mobility change the way we think about very large systems and applications?

- **Observations**
  - Opportunity to "invert" organization of many systems, especially those involving embedded processing, sensors, etc.
  - Need to revisit many issues in: O.S., compilers, networks, fault tolerance, transactions, information management, etc.

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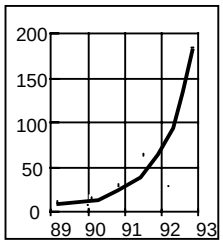
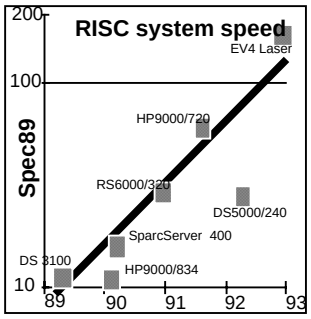
WHAT'S ENABLES ALL THIS? SOFTWARE!



Growth is exponential
plot on semi-log scale



Systems are increasingly software-driven

- Software implements conversion / configuration functions.
- Processing ability grows exponentially.
- Cost of diversity / dynamic configuration is in free fall.

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WHY DOESN'T THIS SINK IN?

Traditional Systems Engineering

- Designers strive for homogeneous systems
  - Do the same thing everywhere
  - Streamline interfaces
  - Why? Cost of converters that bridge technologies
    - example: electrical adapters
- We streamline processes as well
  - Supply chain engineering

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IMPLICATIONS FOR INTELLECTUAL PROPERTY

- **Massive Increase in Rate of Dissemination**
  - Diversity of vehicles / forums?
  - Decrease in “atomic unit” of dissemination (?)
- **Traditional units of Dissemination – Tell a complete story**
  - Books and papers
  - Patent filings
- **New Units of Dissemination – Tell part of a story**
  - Individual steps of a proof (e-mail)
  - Scientific protocols via the Web
  - Sequence entries registered in DNA databases
  - Audio / video clip art?

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IMPLICATIONS FOR COMMERCE? LOOK AT THE WEB …

User … I’m trying to do too many things at once.

Computer … Appearance of doing many things.

Economist … Transaction costs are plummeting.

- Units of transaction decrease / Freq. increases.
- Example – Brokerage commissions.

The (commercial) world is spinning faster!

Increased competition … Less room to hide.

- Market is well-informed wrt supply, prices, etc.

Dynamic supply chains.

- De-engineering?

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BACK UP

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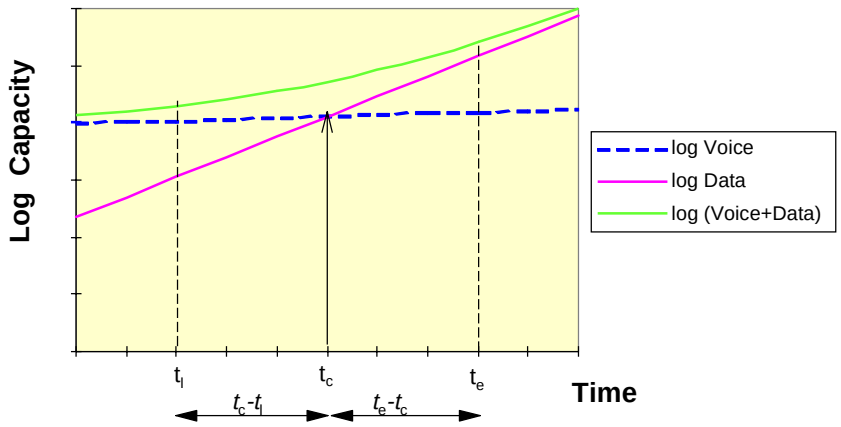
VOICE/DATA TRANSITION MODEL



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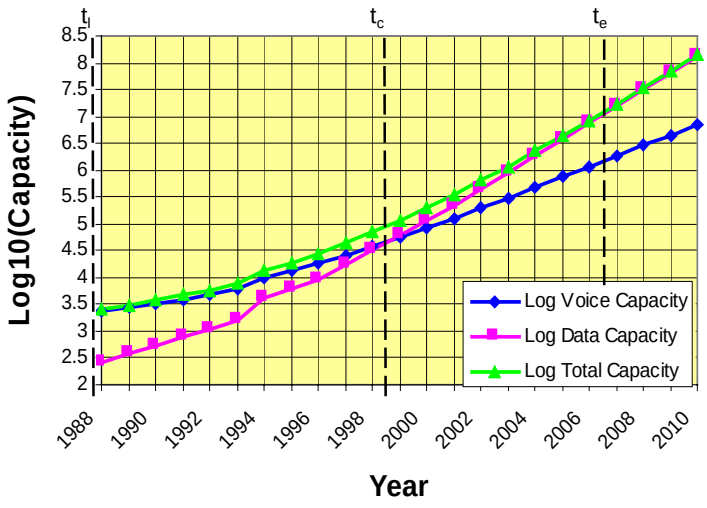
TRANSITION MODEL "RESULTS"



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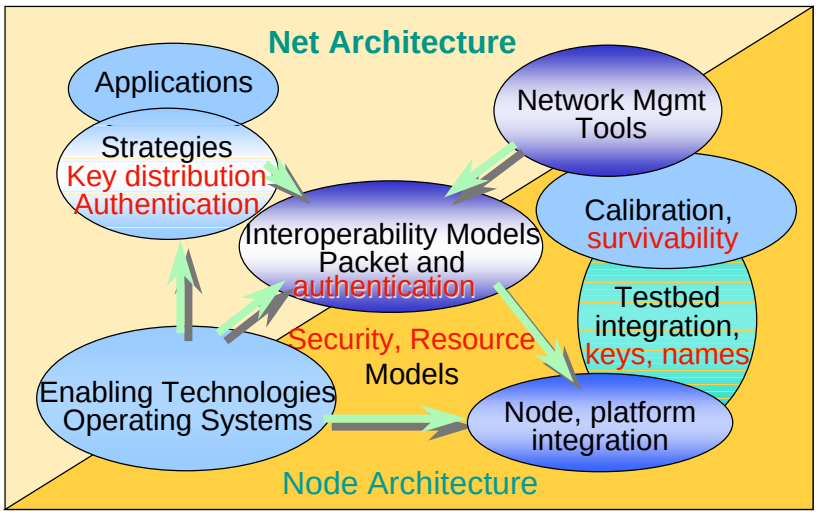
ARCHITECTURAL FRAMEWORK



Security permeates architecture

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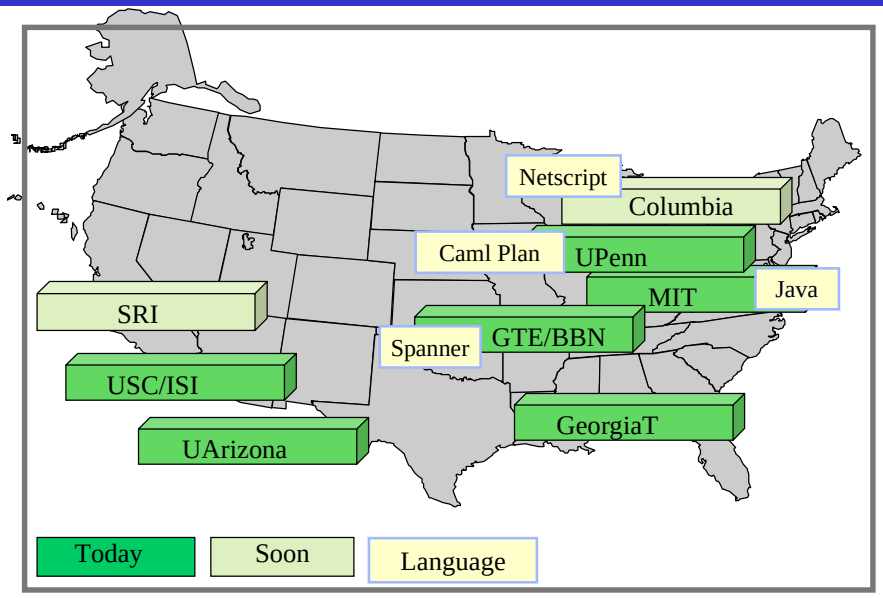
ACTIVE NETS TESTBED TODAY: THE ABONE



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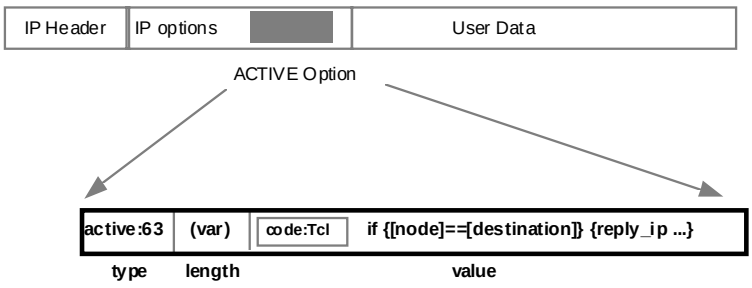
THE ACTIVE IP OPTION – A CHEAP & CHEERFUL PROOF OF CONCEPT



IPv4 / tcl (linux)

Cheap & Cheerful ≈ Quick & Dirty

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USING ACTIVE IP

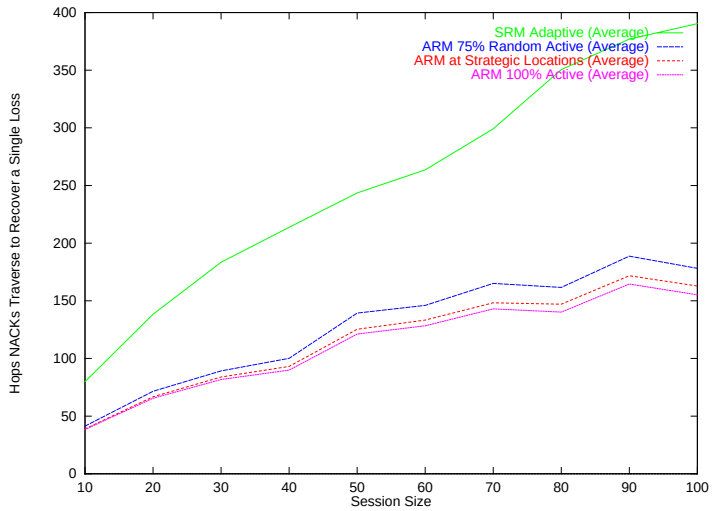
- **node scripting primitives**

Packet	Control	Environment
data	send_ip	node (IP)
replace_data	reply_ip	time
source (IP)	discard	host
destination (IP)	eval [data 0]	mtu

- **network discovery functions and more**

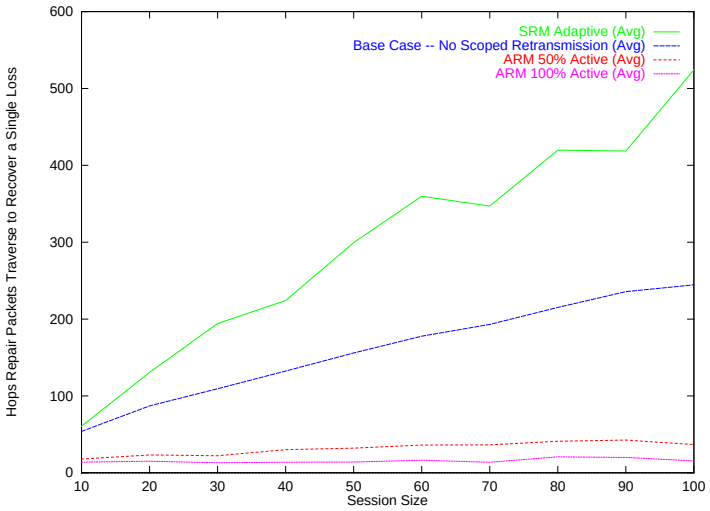
  e.g. trace/ping: reply_ip "[node] [ttl]"
  if {[node]==[destination]} {discard}

NACK BANDWIDTH CONSUMPTION



NACK bandwidth consumption with strategically placed active nodes (loss near source, 1000 nodes, degree 4)

HOPS TO REPAIR A SINGLE LOSS



Hops traversed by repair packets to recover a single loss (random loss, 1000 nodes, degree 4)

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ACTIVE / MOBILE CODE TECHNOLOGIES

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BENEATH THE INTERNET …
… THE IMPORTANCE OF SHARING

Scenario: *User clicks mouse.*
Triggers 10 Mbyte transfer.
Willing to wait 1/2 second.

- **Small Organization (5-10 users).**
  - Need to use 155 Mbps link.
  - Alternative – buy 1 Mbps link and wait 80 seconds!
- **Large Organization of the Future.**
  - 2000 Users, 1 Mbps / user average demand.
  - Buy 2.4 Gbps links (added bonus – volume discount).
  - Up to 15 users can generate simultaneous bursts.
  - 50 to 100 fold cost differential.

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WHAT ABOUT THE LITTLE GUY?
RESIDENTIAL ACCESS?

- **Virtually all channels will be digitized …**
  - Cable Modems (HFC)
  - FTTN + ADSL
  - Wireless – Cellular, PCS, TV, DBS…
- **When are resources bound to subscribers?**
  - startup? subscription time? on demand?
  - can idle resources be re-assigned?
- **Cellularization is a common theme …**
  - Terrestrial systems
    - Drive Fiber to the Neighborhood (Shared)
    - Minimize fixed assignment of resources to individuals.
  - Satellite systems – project cells onto the ground.

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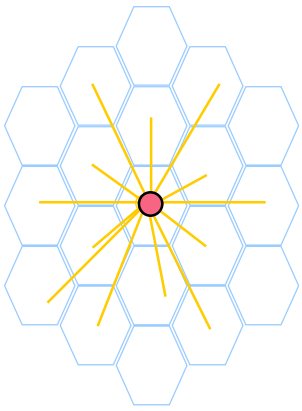
THE CELLULARIZATION OF AMERICA



Cellular Telephony — Shared FTTN, Shared Spectrum

Cable / Coax — Shared FTTN, Shared Coax

ADSL / Twisted Pair — Shared FTTN, Private Loop

FTTN — Shared FTTN, Shared Fiber

Cellular schemes are modern day party lines … with fewer of the nasty side-effects!

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PUTTING THE LAST MILE ON THE CURVE

What are the cost drivers?

- During startup phase
  - minimize capital costs
  - maximize geographic coverage
- During stable phase
  - drive down operating costs
  - plan on 100% penetration
- Impact of Rapid Innovation
  - new technology has lower operating costs
  - plan for continuous renewal (no stable phase)
- Infrastructure cost vs access bandwidth?

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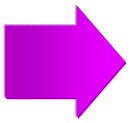
MEGABITS FOR THE MASSES…

Dynamic sharing

- Appearance of speed through dynamic allocation of shared resources.
- Party-line 2000

Heterogeneity

- Mix & match technologies
- Contrast with: do the same thing everywhere.



Virtualization of Channels

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